Prediction of the Low Frequency Wave Field on Open Coastal Beaches

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LONG-TERM GOALS

The long-term goal of this study is to arrive at a predictive understanding of the time varying circulation in the nearshore region given only information about the incident wave field and bottom bathymetry. Predictions should include information about the kinematics of low frequency motions (their wavenumbers and frequencies) as well as information about their dynamics (energetics).

OBJECTIVES

The scientific objectives of the study are related to gaining an understanding of the important features of the nearshore circulation field, so that quantitative predictions about the circulation field at a given site can be reliably made. Specific objectives include: 1. The assessment of the impact of specific features of wave groups on edge wave development and the prediction of the finite amplitude edge wave field resulting from a balance between the wave group forcing and dissipation mechanisms. 2. The assessment of the degree to which non-uniformities in the bottom bathymetry (both abrupt and gradual) affect the resulting low frequency wave climate. 3. The assessment of the importance of interactions between different modes of time-varying motions in the nearshore region, as well as interactions between these modes and the incident wave field. 4. To arrive at a predictive understanding of low frequency motions.

APPROACH

The approach is to use a numerical model to assess our understanding of time-varying circulation in the nearshore region. The finite amplitude behavior of low frequency motions in the nearshore region is a function of a balance between processes that generate these motions and processes that dissipate them. The approach used here is to isolate several generation, dissipation processes as well as processes affecting the evolution of the motions in a modeling effort and start with the simplest possible theory to model the processes. More complicated and full treatments are introduced in a step-by-step fashion resulting in an understanding of the effects of the processes and their parameterizations on the resulting circulation field.

We are utilizing a model that solves the time-dependent shallow water equations with additional terms to account for the effects of forcing and damping (Özkan-Haller and Kirby, 1997). Although only valid in shallow water, these equations can model the leading order behavior of both low frequency gravity

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motions (edge waves) and vorticity motions (shear waves). Eight partial differential equations are solved simultaneously to obtain the evolution of eight unknowns; namely, the phase-averaged water surface elevation, the phase-averaged cross-shore and longshore velocities, the horizontal shoreline runup due to low frequency motions, the incident wave energy, the incident wave wavenumber, the local incident wave direction, and the water depth. The effects of bottom friction, turbulent momentum mixing, incident wave transformation and forcing, wave-current interaction and arbitrary bottom movement, are included in a rudimentary fashion. We begin our modeling effort by generating edge waves and shear waves in idealized conditions, and progressively move to more realistic situations where these motions are allowed to coexist and interact.

WORK COMPLETED

We have completed the implementation of an equation governing the behavior of the time-varying incident wave energy in order to simulate the evolution of incoming wave groups. We subsequently analyzed the generation of edge waves by a bi-chromatic wave field, including the effects of nonlinear wave interactions as well as the effect of a moving breakpoint (Lippmann *et al*., 1997). We successfully generated various edge wave modes of finite amplitude and have isolated the effects of nonlinear generation mechanisms and generation due to a moving breakpoint. Also under investigation was the half-life of the generated waves. A finding suggested that finite amplitude edge waves could exist in both a high forcing-high dissipation environment as well as a low forcing-low dissipation environment. We have analyzed measurements obtained previously on a pocket beach to gain information about the dissipational climate in which edge waves may exist.

We have completed the implementation of the time dependent equations that approximate the behavior of phase-averaged properties of the incident waves; namely, the incident wave energy, the wavenumber and the local angle of incidence. The energy equation for the incident waves is used to model the former while the conservation of wavenumber principle is introduced to model the latter two variables. These model equations include effects of the current velocities. In this manner the forcing of wave-induced currents is modeled while taking the effects of the generated currents on the wave field into account. We have analyzed wave-current interaction effects in environments with varying amounts of dissipation due to bottom friction. We concentrated on the flow properties of the resulting currents as well as propagation speeds of the resulting motions. Also of interest was the effect on the shoreline runup.

We have completed the derivation and solution of an analytical model to isolate unstable behavior in the surf zone due to the interaction of unsteady currents and the incident wave field. Utilizing this linear instability model we have isolated unstable modes for obliquely incident waves as well as normally incident waves on both planar and barred beaches. We have analyzed the effects of wave-current interaction and have isolated the dominant mechanisms through which the dynamics is affected.

Finally, we have incorporated a simple sediment transport formulation along with an equation governing morphology evolution to pinpoint the existence of unstable morphological modes that arise when interactions between the wave field, the circulation and the morphology are taken into account.

RESULTS

Our simulations on the nonlinear evolution of shear instabilities of the longshore current suggest that the onset of the instability is delayed when wave-current interaction is taken into account (see Özkan-Haller and Li, 2003). This finding suggests that the initial linear growth rate of the instability is reduced by the presence of wave-current interaction. A way to isolate the mechanism by which this occurs is to carry out a linear instability analysis of the system of seven equations that form the basis for the nonlinear model that was utilized. We start by analyzing the linear instability of a simplified system of equations assuming wave-current interaction can be neglected and the low frequency motions are neither actively forced nor dissipated. In this case, the linear instability analysis gives information about both the gravity and the vorticity modes that exist as solutions to this system. The instability analysis assumes that the frequency of the solutions can be a complex number, where a positive complex part indicates initially exponentially growing modes such as shear instabilities of the longshore current. Neutrally stable modes such as edge waves will be characterized by a zero imaginary frequency component. Figure 1 shows the resulting eigenvalues for a wavelength of ~105 m for a situation involving a plane beach and a peak longshore current speed of about 1 m/s. In this case, the linear instability analysis gives rise to several edge wave modes (that have negative growth rates since they decay in the presence of friction) along with a shear instability mode (that displays a positive growth rate. Also evident is the presence of a number of spurious modes near the origin. These modes are generated either due to rapidly varying solutions that are not adequately resolved by the discretization (such as incident gravity waves) or by a continuum of physical solutions that can not be expressed within a discretized model. The occurrence of such spurious modes in the solution of linear instability problems is commonly cited in the literature and methods to isolate them from true physical solutions exist. We utilize a method based on the convergence of the eigenvalues as the number of discretization nodes is increased. Solutions for different number of nodes are displayed with different symbols in Figure 1, co-incident symbols indicate a convergent mode.

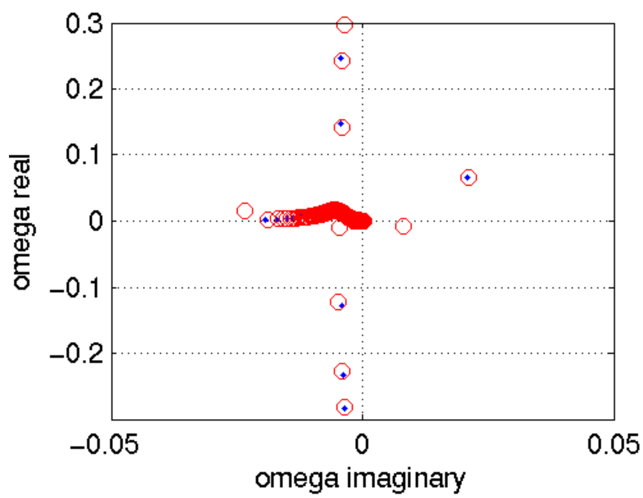

Figure 2: Real part of the radial frequency versus the imaginary part of the radial frequency for motions at radial wavenumber k=0.06 rad/m. Positive imaginary frequencies indicate an exponentially growing mode; negative imaginary frequencies indicate exponentially decaying modes. Edge waves display negative growth rates (due to frictional decay), the shear instability mode displays positive growth rate. Close to the origin there are several instability modes that represent morphological instabilities.

Using such a linear instability model we can isolate the effect of wave-current interaction on the linear growth rate of a mode. We find that wave-current interaction indeed reduces the growth rate of the instabilities (see Figure 2) at almost all wavenumbers, consistent with nonlinear model results, but does not significantly effect the propagation speed of the motions (not shown). We can also isolate the interaction mechanism that is responsible for this reduction: the circulation does work on the wave field (e.g. causing it to shoal and refract around positive cross-shore currents) and hence looses energy.

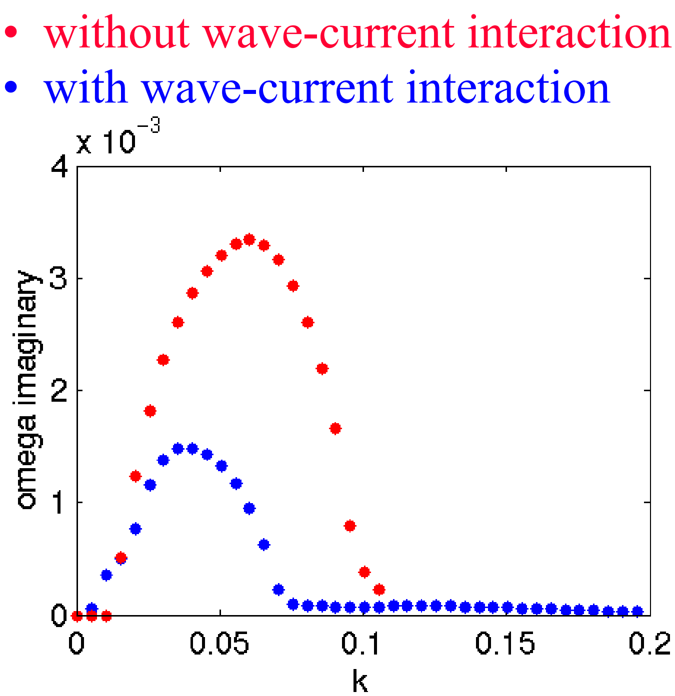

Figure 2: Growth rate versus alongshore wavenumber with (blue) and without (red) the effects of wave-current interaction. Wave-current interaction reduces the growth rate of the instability. This reduction can largely be explained by the effect of work done by the circulation on the waves (pink).

Solution of the linear instability analysis also gives rise to unstable morphological modes. Modes of different characteristics exist. The spatial structure of the perturbation to an initially planar beach is shown in Figure 3. The concurrent circulation field is also shown. The linear instability gives rise to the formation of a crescentic bar, with growth rates corresponding to an e-folding time scale of about 10 days and alongshore propagation speeds of about 3m per day, which are realistic. Shorter scale unstable modes also exist and give rise to features reminiscent of transverse bars (not shown).

Two publications related to the results outlined here are currently near submission.

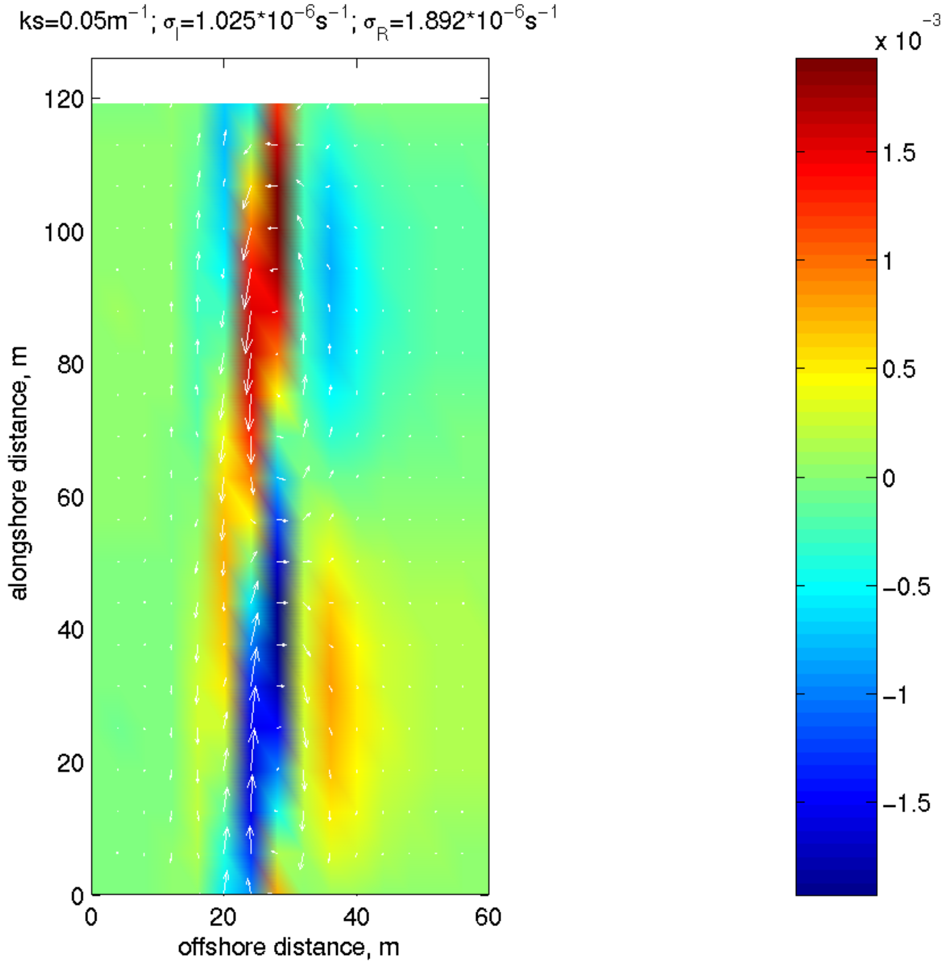

Figure 3: Spatial characteristic of the perturbation to an initially planar beach over an approximately 120m alongshore length scale. The outer edge of the surf zone is ~40m away from the shoreline. The circulation field is indicated by the arrows and is in the form of a rip current existing at the low point of the perturbation (the "hole") and flow returning over the high point (the "hump").

IMPACT/APPLICATIONS

This study sheds light on the processes that are important in the low frequency range of the energy spectrum, such as interactions between low frequency waves and response of the low frequency environment to external forcing. This study can also serve as a benchmark for other studies that do not explicitly resolve the time-varying low frequency wave field but instead focus only on the mean circulation. Results obtained here should also be relevant to studies that are not restricted to low frequency motions, but where the low frequency motions are embedded in higher frequency oscillations, making the processes difficult to identify.

TRANSITIONS

The work on the project will lead to a robust modeling tool which is capable of predicting the time-varying circulation field including effects such as incident wave forcing, bottom friction, momentum mixing and wave-current interaction. The model code is available to the engineering and science communities.

RELATED PROJECTS

The effect of edge waves and shear waves on the evolution of bathymetry is being investigated as part of the ongoing NOPP project (Lead P.I. J.T. Kirby) "Development and Verification of a Comprehensive Community Model for Physical Processes in the Nearshore Ocean". A version of the code developed here is utilized in the project "Modeling Beach Morphology Changes Coupled to Incident Wave Climate and Low Frequency Currents" (P.I. J.T. Kirby). Aspects of unsteady currents in the nearshore zone are the topic of the study "Nonlinear Time-Dependent Currents in the Surfzone" (P.I. D. Slinn).

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